Solar Photovoltaic Module Retirement in the State of Washington

Preliminary Analysis and Recommendations For Further Study

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Executive Summary

Due to the decreasing cost of solar photovoltaic (PV) modules and the push to reduce carbon emissions, national solar PV installations have increased rapidly. Solar is the fastest growing energy source in the U.S., representing 43% of added capacity in 2020.[1] However, key clean energy technologies such as solar panels, wind turbines, and lithium-ion batteries are also material-intensive.[2] Furthermore, discarded solar panels may be hazardous to the surrounding environment, due to the presence of trace heavy metals such as silver, lead, and cadmium if disposed of incorrectly.[3] The recycling and reuse of solar PV modules is therefore critical to avoid improper disposal, reduce the environmental and social impacts of energy production, conserve resources, and reduce resource constraints by enabling the domestic recovery of high value raw materials.[4]

To support the development of a sustainable end-of-life pathway for PV modules in Washington State, this report provides an overview of the solar PV market in the state, then estimates the timing of future module retirements, as well as the volume and composition of the corresponding waste stream based on historical installation data. This research represents phase 1 of 3 recommended research segments intended to inform discussion regarding Washington State's Photovoltaic Module Stewardship and Takeback Program, which was originally created by SB 5939 in 2017 (codified as RCW 70A.510)[5], amended with ESHB 2645, then delayed by the 2021 Legislature for two years by HB 1393 to allow for analysis and quantification of the potential future product and waste stream.

To date, there is currently no federal policy regulating PV recycling in the U.S., and only four states have laws or regulations that directly address the management of end-of-life modules. North Carolina and New Jersey both established commissions to study end-of-life management options, and California classified panels as Universal Waste in order to ease the regulatory burden of shipping and handling. Washington is the only state that has created a stewardship program with producer responsibility.[20]

Key Findings:

Status of solar PV market in Washington State

As of 2020, there were a total of 264 MW installed in Washington State, representing .26% of the total installed capacity in the U.S. The Solar Energy Industry Association (SEIA) expects the state to install an additional 834 MW of solar modules in the next five years, an increase consistent with the national increase in solar deployment.[1] According to available data, 42 manufacturers have sold into Washington State since 1999, with the 2018 and 2019 market dominated by three companies: Itek Energy (no longer manufacturing in, or selling into the state), Hanwha Q-cells, and Silfab Solar. The majority of installations are small-scale rooftop systems under 1 MW, and were supported by subsidies from the state. Those subsidies have since been terminated for new installations.

Expected panel retirement

To model the timing and volume of PV retirement, we forecast installed capacity through 2025 under low, medium, and high sales scenarios. The end-of-life is modelled assuming 30- and 35-year average lifespans. Under the medium sales scenario and assuming a 35-year lifespan, the volume of retired modules will reach 1 metric ton (MT) in 2047. Retirement begins to rapidly increase between 2049 and 2054. The volume of the waste stream from modules installed through 2025 reaching 7.22 to 10.49 MT, depending on the installation and lifespan scenario.

Material composition of waste stream

The majority of materials by weight retired consist of glass (69%) and aluminum (12%) from the protective front sheet and frame. The remaining 19% of the waste stream is expected to contain trace amounts of polymer, copper, lead, tin, polyvinyl fluoride, silicon, and silver. These materials are used in the silicon cell, backsheet, encapsulant and other components. The 2019 Product Stewardship Plan produced by the Washington State Department of Ecology (Ecology), pursuant to the original law, states that manufacturers must recycle at least 85% of the modules by weight,[6] which is nearly met through recycling the aluminum and glass alone. This indicates that as it is currently written, the Plan may not encourage the recovery of key elements of interest such as silicon, copper, or silver.

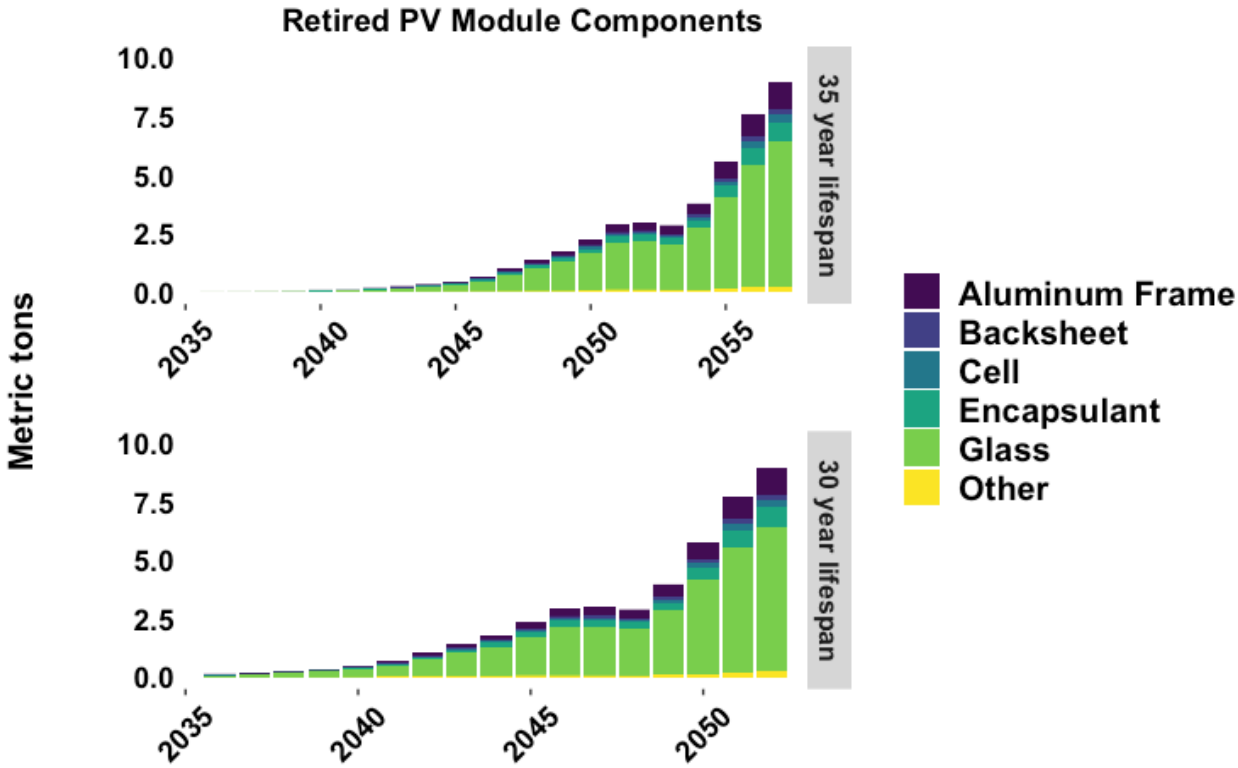

Figure ES1:
The metric tons of retired solar monocrystalline PV modules in Washington that are sold between 1999 and 2025. The data represent the medium sales scenario.

Orphaned modules

Because the original plan only applies to residential modules installed after July 1, 2017, a subset of "orphaned" modules installed to date will not be covered by House Bill 1319 or any other program currently in place in the state. An amendment to the original law in ESHB 2645 in the 2020 Legislature added utility scale modules to the product stewardship program. Parsing the retired modules by their qualification under the House Bill 1319 demonstrates that of total modules sold to date, slightly more than half are not covered by HB 1393 (132.5 MW of 264.4 MW), and that percentage and volume may increase based on future opt-out decisions by manufacturers. Due to the projected increase of sales within the next five years, about 83% of all modules installed will be covered by the policy by 2025, or an estimated 47.86 MT in the medium sales scenario.

Looking ahead, this means that the majority of materials retiring will not be covered by the policy until 2045 to 2050, depending on the assumed lifespan. This represents .46 of 1.78 MT of retired modules in 2050, assuming a 35-year lifespan. After these years, the covered panels represent the majority of the retired weight of modules.

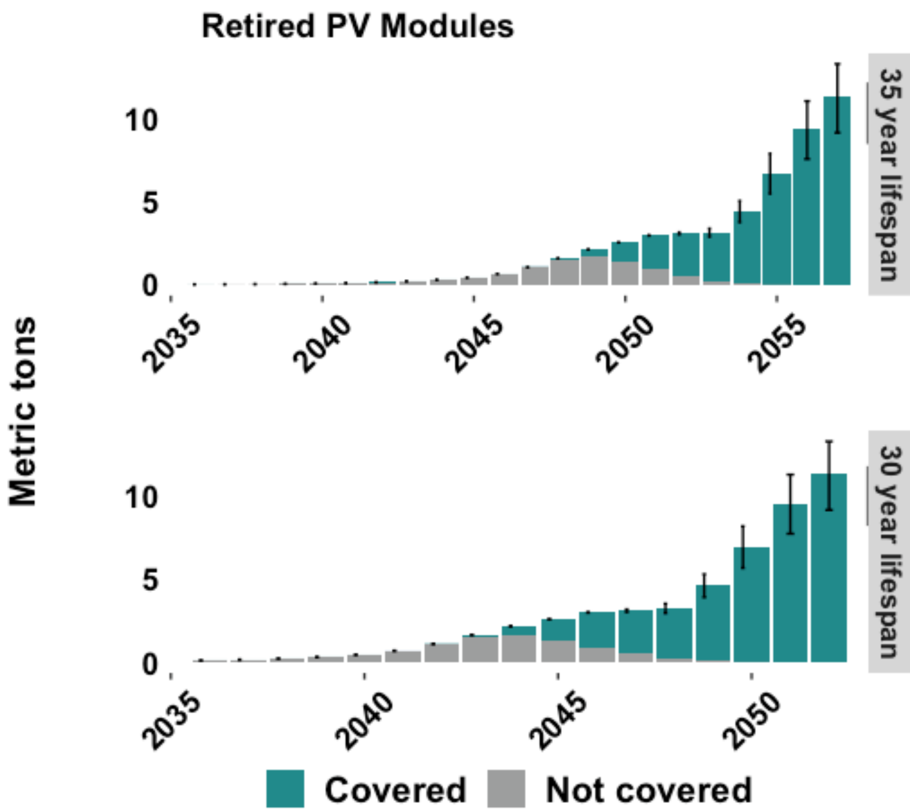

Figure ES2:
The metric tons of retired solar PV modules in Washington that are sold between 1999 and 2025. The columns represent the medium sales scenario, while the error bars represent the difference in the high and low sales scenarios.

Glossary

Silicon solar cells: Light-absorbing wafers and silver, aluminum, or copper conductors that extract direct current (DC).

String connector ribbons: Cells are interconnected with copper wire or ribbon, then sealed within a protective polymer sheet (encapsulant).

Encapsulant: The components used in laminate construction and contain an outer polymer layer which serves to protect the cells from the elements.

Aluminum frame: The laminated modules are typically framed using aluminum extrusion profiles for mechanical rigidity, and most are rated to withstand front- and rearside mechanical loads up to hurricane-level windspeeds.

Backsheet: The insulating back of the module which is typically made from a polymer film laminate that adheres to the encapsulant.

Junction box: The cells are connected at one side of the modules by the junction box which is used to connect modules into a system.[7]

Bifacial panels: Panels which produce energy from both the front and back side.

Monofacial panels: Panels which produce energy from just one side.

1. Introduction

To meet climate goals and reduce global warming, renewable energy sources such as solar photovoltaics (PV) are needed to replace traditional energy sources. However, key clean energy technologies such as solar panels, wind turbines, and lithium-ion batteries are also material-intensive.[2] Furthermore, discarded solar panels may be hazardous to the surrounding environment, due to the presence of trace heavy metals such as silver, lead, and cadmium if disposed of incorrectly.[3] Recycling and reuse are therefore essential to reduce the environmental and social impacts of energy production. In addition to reducing impacts from production and disposal, recycling and reusing PV can reduce resource constraints by enabling the domestic recovery of high value raw materials.[4]

Recognizing the importance of proper end-of-life management, the Washington State Senate passed SB 5939 in 2017 that included the Photovoltaic Module Stewardship and Takeback Program. (Chapter 70.510 RCW). The bill requires manufacturers to finance the takeback and recycling of modules at their end-of-life, and applies to all residential panels installed after July 1, 2017 and all utility scale panels installed after the effective date of the act in 2020. Because the original plan only applies to residential modules installed after July 1, 2017, a subset of "orphaned" modules installed to date will not be covered by HB 1319, or any other program currently in place in the state. An amendment to the original law in ESHB 2645 in the 2020 Legislature added utility scale modules to the product stewardship program, but did not specify the panel date of installation that applies. Without including a date of installation, which indicates that panels installed after that date would thereafter be covered by the program, it is assumed that the utility scale panels installed in 2020 and after are covered.

Ecology was tasked with developing guidance for the solar PV module stewardship plan while working with manufacturers, stewardship organizations, and other stakeholders. Manufacturers were originally required to prepare and submit a stewardship plan by January 1, 2020, and, if Ecology had not approved the plan by January 1, 2021, the manufacturer would have been prohibited from selling their modules into the state thereafter. The prohibition includes a penalty of up to $10,000 per panel sold on the manufacturer, even if a distributor or installer sells the panel.

The 2020 Legislature adopted HB 2645, which made important changes to the program by: 1) delaying implementation of the program, 2) specifying a July 1, 2023 date for prohibition of module sales if the manufacturer did not have an approved stewardship program, and 3) adding utility-scale modules to the product stewardship program. HB 2645 also contained a provision that established a task force and a study to quantify the modules that were to be covered by the program and modules installed prior to July 1, 2017 that are not covered. The task force and funding for the task force were vetoed by the Governor, due to the budgetary constraints of the looming pandemic. Finally, to prevent the stewardship program from creating uncertainty for manufacturers selling modules into the state, HB 1393 was adopted by the 2021 Legislature, effective July 25, 2021. The bill delayed implementation of the product stewardship plan by an additional two years, without any additional modification to the program.

This study was funded by Ecology and is intended to support establishing sustainable end-of-life pathways of solar PV in Washington State by informing the development of regulation, process, and timetables implemented by RCW 70A.510. This report provides background information on module composition and recycling, describes the market and landscape of solar PV in the State of Washington, and finally estimates of the volume, composition, and timing of future module retirements. This represents phase 1 of 3 recommended research segments.

2. Overview of solar PV modules and end-of-life solutions

2.1 Material composition

A typical solar PV system can be broken down into its component parts: cell, panel/module, and array. The smallest foundational element of a PV system is the solar cell, which is generally composed of light-absorbing wafers and silver, aluminum, or copper conductors that extract direct current (DC). The light-absorbing wafers are made from semiconductor material, most commonly silicon. Finished cells are interconnected with copper wire or ribbon, then sealed within a protective laminate to form a module. The components used in laminate construction, such as the glass and polymer encapsulant, are similar in design and manufacturing to car windshields. In addition, they contain an outer polymer layer which serves as a high durability, outdoor-rated dielectric material to protect the cells and electrical connections throughout module lifetime. The laminated modules are typically framed using aluminum extrusion profiles for mechanical rigidity, and most are rated to withstand front- and rearside mechanical loads up to hurricane-level wind speeds. Figure 1 depicts a panel/module consisting of four cells.
To turn one or more modules into a functional PV system, they are equipped with additional ancillary components, such as wires, batteries, mounting equipment, and an inverter. The scope of this analysis is limited to PV modules, as specified by the legislation; therefore it does not review the other materials in a complete solar PV system such as mounting equipment, inverters, or batteries.

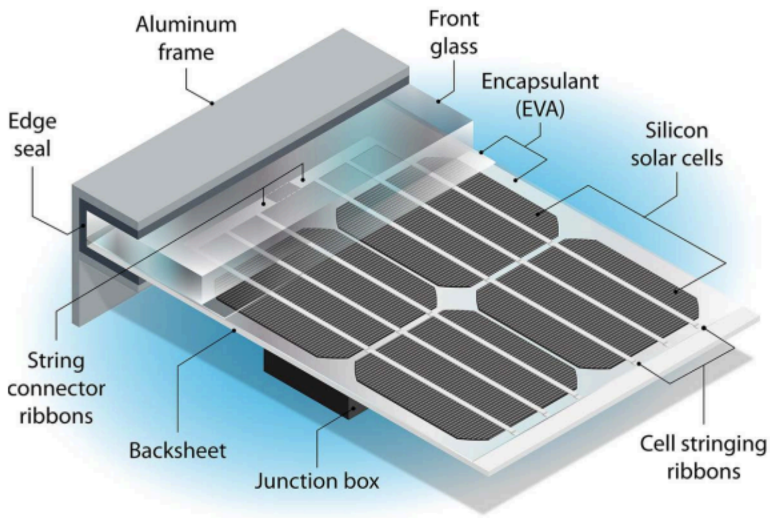

Figure 1:
A monocrystalline solar PV panel and the component parts.
Original source: NREL (2016).[7]

The exact material composition of PV modules varies by the type of semiconductor, the manufacturer, the year manufactured, and other factors. The two most common semiconductors are crystalline silicon (either monocrystalline or polycrystalline), and amorphous silicon, also known as thin-film cells. Of the two, crystalline silicon semi-conductors are the most common, due to their higher efficiency.[8]

Most modules are monofacial, meaning they produce energy from just one side of the panel, while bifacial modules are a newly emerging technology that produces energy from both sides[9]. The International Technology Roadmap for Photovoltaic reports that 30% of world solar PV sales were bifacial in 2020 and they forecast 80% will be bifacial in 2031. While bifacial modules are yet to be common in the State of Washington, they can be expected to increase over the next decade.[10] A typical monofacial panel is manufactured using a high-strength tempered glass front sheet with anti-reflective/anti-glare coating, and an insulating backsheet made from a polymer film laminate that adheres to the clear polymer layer encapsulating the solar cell circuit.

There are variations in the materials used for PV backsheet designs. Older generation products used polyethylene terephthalate (PET) sandwiched between polyvinyl fluoride (PVF) known commercially as Tedlar. In more recent models, the PVF has been replaced with polyvinylidene difluoride (PVDF) and commercially known as Kynar. The presence of PVF and PVDF is a concern for end-of-life management, as the recycling process may require scrubbing to prevent the release of hydrogen fluoride (HF) gas. In response, the company Coveme has developed a more environmentally friendly fluorine-free backsheet which uses UV-stable PET and polyethylene (PE) instead of fluorinated polymers.[11]

The material composition will change over time, due to industry trends and innovation towards more efficient and environmentally friendly panels. [12] Observed trends that are predicted to continue include:

- Thinner cells, which decreases the use of cell materials, but may also increase the likelihood of cells being cracked upon retirement [12](Heath et al., 2020).

- The declining use of silver, which has already decreased by 70% since 2010. Silver is expected to be increasingly replaced with copper in the future, which will lower the value of recoverable materials.[13]

- Decreased lead content through the use of lead-free solder, which will reduce the toxicity of the waste stream. Over 90% of the soldering contains lead, and this is predicted to decrease to slightly above 70% in 2050.[10]

- Bifacial panels which require less aluminum on the rear-side, slightly more silver, and in some cases may have glass instead of foil as the backsheet.[10]

- Backsheet materials evolving away from fluoride containing materials, which will reduce the environmental burden of end-of-life processing.[10,14]

This study uses a bill of material provided by Silfab to estimate the material composition of a 370-380Wp module which is shown in Figure 2. Table A1 in the Appendix contains a detailed list of this information.

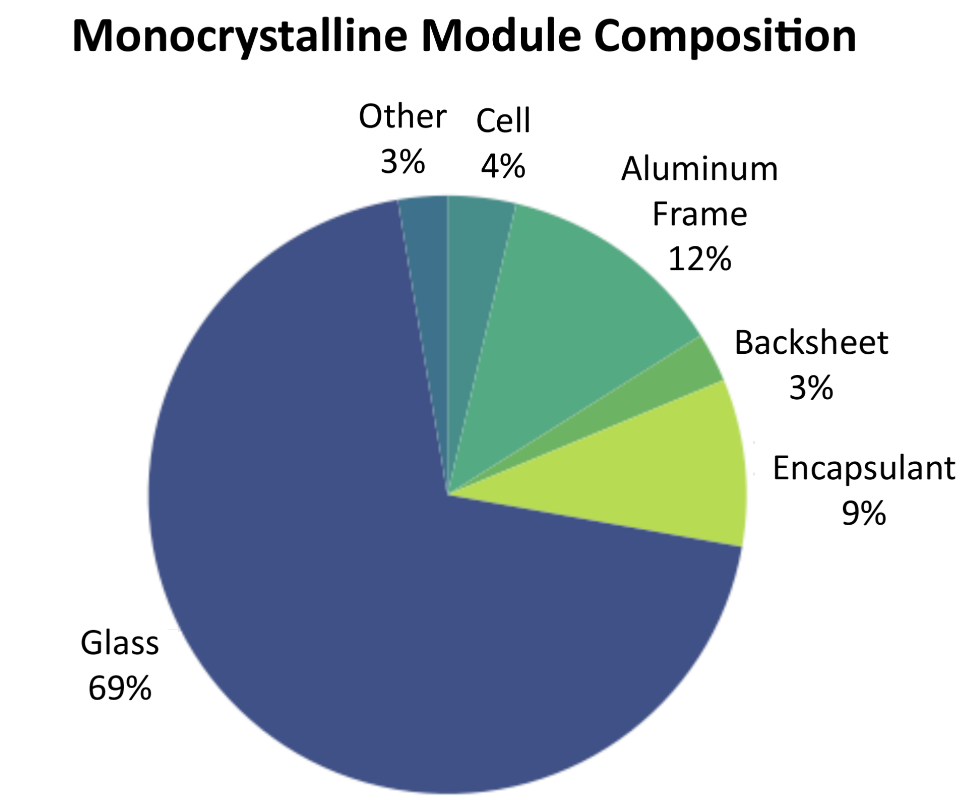

Figure 2:
The material composition of monocrystalline modules. The data was provided by Silfab Solar Inc.

2.2 Module recycling

Before PV modules can be recycled, they are typically separated from other balance-of-system components such as racks, inverters, and cabling. These balance-of-system components can be recycled at established e-waste and scrap metal recycling facilities, while the modules are sorted, stored, and transported to a separate recycling facility.

Once modules have arrived at a specialized facility, the first step is mechanical treatment to remove the aluminum frame, which can also be recycled as scrap metal. Next, the glass is separated from the silicon wafer through physical, thermal (heat), or chemical treatment. Finally, chemical and electrical treatment is required to separate the cells and purify the recovered silicon wafer and specialty metals such as silver, tin, lead, and copper. Technology to recycle aluminum and glass is commercially available; however, integrated processes to recover all specialty and trace materials in usable form are still in the demonstration or pilot phase.[12] The first facility dedicated to Si module recycling was built in France in 2018.[15] In some cases where modules are not sent to specialized facilities, recyclers do not separate the component parts such as aluminum or glass, and instead shred the entire module. [16]

SEIA initiated a national voluntary solar recycling program in 2016 and oversee a growing partner network of recycling companies in numerous states.[17] As of January 2020, the network did not include a partner company in the State of Washington, although it had been identified as a priority “next phase” state. The companies in the network are primarily electronic waste and glass recyclers who recover easily accessible, bulky materials such as glass, aluminum, and copper wiring.[16] However, there are at least two companies in the U.S. that specialize in PV module recycling: Recycle PV Solar and We Recycle Solar. Recycle PV Solar has a facility in Nevada that accepts monocrystalline and polycrystalline panels, but not thin film. They also accept usable intact solar panels for repurposing. We Recycle Solar has a facility in Nevada and accept monocrystalline, polycrystalline, and assorted thin film PV cells, as well as ancillary equipment such as batteries, inverters, and mounts and racks. The costs for services provided by both companies are quote-specific, and it is important to note that the party disposing of the solar panel will also be required to pay the costs of decommissioning the system, shipping, and packaging.

2.3 Module reuse

Most modules are still able to produce power when they reach the end of their warrantied life, which points to the potential for reuse prior to recycling. This is particularly relevant in cases where a roof may be replaced while the solar panels are still producing at high efficiency, but a user may still choose to upgrade or replace their system. Where possible, reuse is preferable to recycling, since it requires fewer processing steps and a higher potential to generate revenue. Proponents of reuse point to the sustainability benefits, such as extending the product lifetime and avoiding landfilling or premature recycling. Reused or repurposed modules have also been proposed as an affordable solution to expand energy access in remote areas.[18] However, the topic has not been well studied and additional research is needed to quantify the expected quantity of modules that would be suitable for repurposing in terms of technical performance, as well as logistical feasibility. While the cells may still produce sufficient energy to be repurposed, transporting modules is uniquely difficult, due to the high potential for glass to break or cells to crack.[19] The economics of module reuse are also unclear, as rapid technological development means higher efficiency panels are increasingly available at lower prices. Furthermore, exporting used modules effectively places the burden of disposal on the importing country, which may not have the infrastructure required to safely dispose of them.

2.4 Existing end-of-life policy

There is currently no federal policy regulating PV recycling in the U.S., and only four states have laws or regulations that directly address the management of end-of-life modules. North Carolina and New Jersey both established commissions to study end-of-life management options, and California classified panels as Universal Waste in order to ease the regulatory burden of shipping and handling. Washington is the only state that has created a stewardship program with producer responsibility.[20]

In Canada, British Columbia (B.C.) solicited feedback on expanding its Extended Producer Responsibility (EPR) effort to include electronic and electric products, including electric vehicle batteries and solar equipment in the fall of 2020. They received twelve public comments indicating support for solar panel EPR, and have stated that the feedback will be included as part of a multi-year recycling strategy; thus, no specific regulations or details of implementation have been announced.[21] In Alberta, the provincial government launched a pilot program that expands electronics recycling to include additional products, including solar panels. The pilot approved the Alberta Recycling Management Authority (ARMA) to provide funding to municipalities that can be used to collect up to 24,600 MTs of products that were not previously eligible under the electronics recycling program.[22]

To date, the EU is the only territory to have adopted comprehensive end-of-life regulations specifically for solar panels, including collection and material recovery targets. Under the revised Directive on Waste Electric and Electronic Equipment, producers must collect and recycle at least 85% of modules free of charge. After 2018, the directive requires 85% of the material collected by weight to be recovered through recycling. Recycling in the EU is managed by an industry stewardship organization called PV Cycle, that now offers waste management and legal compliance services for companies internationally. [23]

3. Background on Solar PV landscape in Washington

3.1 Market size

As of 2020, the State of Washington had a total installed capacity of 264 MW (see section 4.1 for calculations). SEIA expects the state to install an additional 834 MW in the next five years, an increase consistent with the national increase in solar deployment.[1] The rapid growth of solar energy deployment in Washington has been supported by a robust state incentive program and the extension of the federal solar Investment Tax Credit (ITC), a 26% tax credit which applies to both residential and commercial solar. The state incentive program is now closed to new program participants. Due to a planned phase down, the tax credit is planned to decrease to 22% in 2023 and 10% for commercial and 0% residential in 2024.[24]

Despite its rapid growth, Washington is a relatively small percentage of the U.S. solar market, representing .26% of the installed capacity in 2020. By comparison, California – the leading state in installed capacity – represents 32%.[1]

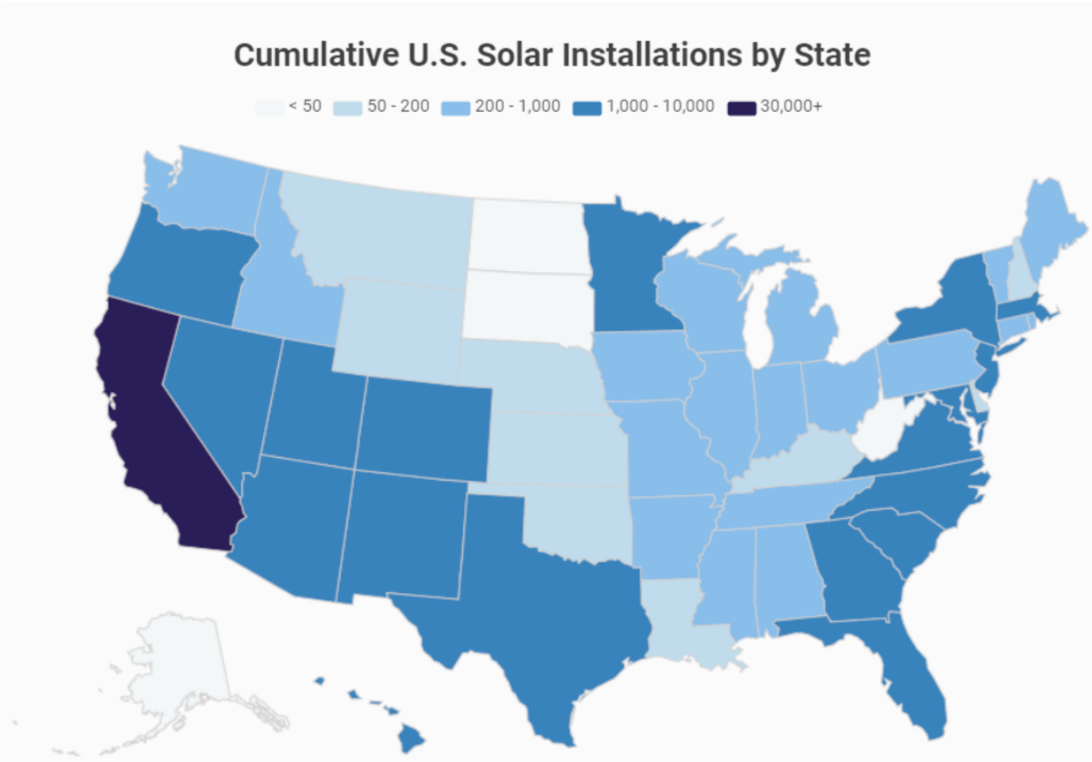

Figure 3:
The cumulative U.S. solar installation by state. Source: SEIA/Wood Mackenzie Power & Renewables U.S. Solar Market Insight 2021 Q2[1]

Most Washington state solar capacity consists of small-scale rooftop solar installations that are less than 1 MW[1]. There is a total of 32.78 MW of utility scale solar with the largest to date facility at 27.8 MW and built in 2018 in Lind, Washington (see Figure 4).[25]

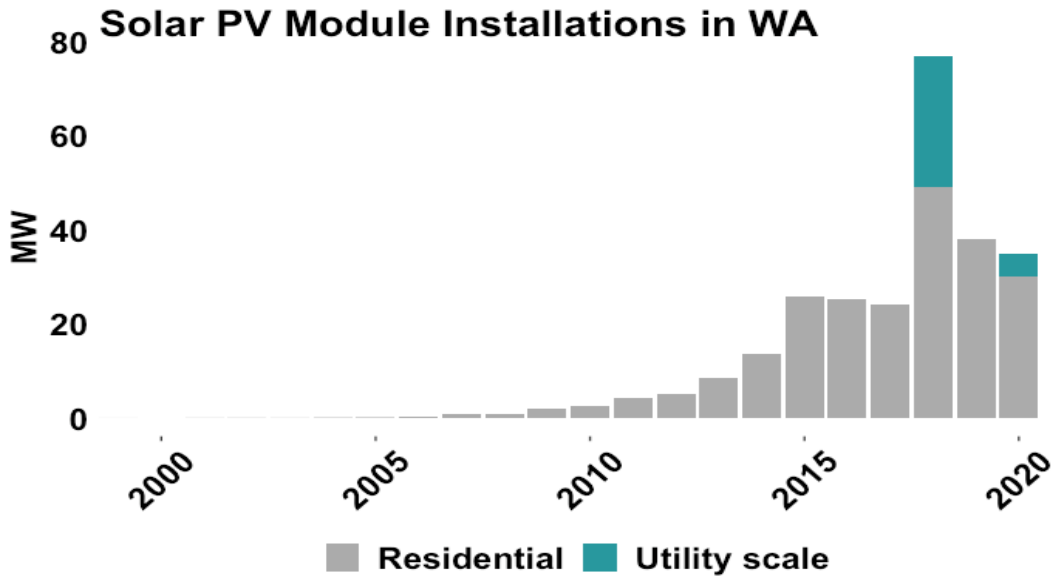

Figure 4:
Solar PV installations within the State of Washington between 1999 and 2020. A total of 264.41 MW installed with 32.78 MW utility scale and 231.63 MW of residential solar PV.

3.2 Relevant actors

Manufacturers

Manufacturers, also referred to as product or equipment manufacturers, produce the physical components of a PV system, such as the panel, inverter, batteries, and framing. The top known panel manufacturers that have sold into the State of Washington are Silfab and Hanwha Q Cells. Silfab Solar is an Ontario-based company that has manufactured modules at the former Itek Energy facility in Bellingham, WA since 2018 (however, Silfab did not purchase the brand or any of Itek's liabilities or warranties, only the manufacturing line), and recently expanded into a second facility in Burlington, WA, for a current in-state manufacturing capacity of approximately 300 MW/year. Hanwha Q Cells operates a facility out of Dalton, GA, and is headquartered in Seoul, South Korea.[25]

The bulk of the product stewardship requirements outlined in the legislation apply to manufacturers. "Manufacturer" is further defined in RCW 70A.510. (2)(e), which among other definitions, specifies that the category includes importers of PV modules, and parties who sell modules acquired from importers if they elect to register as the manufacturer.

Distributors

Manufacturers typically sell to distributors, who primarily provide the services of purchasing, warehousing, and distributing equipment, although some also offer supply chain management and customized system design. Distributors are essentially a middleman between product manufacturers and installers.

RCW 70A510. (2)(c) defines "distributor" as "a person who markets and sells photovoltaic modules to retailers in Washington."

Installers

Typically, when people refer to "solar companies," they are talking about installers. RCW 70A.510 (2) (d) defines installer as "a person who assembles, installs, and maintains photovoltaic module systems." There are hundreds of installers in North America, ranging from small, local companies to national-scale. Installers sell PV systems to customers, such as homeowners or businesses, which requires designing a system to fit the needs of the customer and procuring the necessary equipment. Some companies have their own crews to perform the physical installation of the system, while others use subcontractors.

When a system reaches end-of-life, it is likely the installer or their subcontractor who will remove the panels in bulk and store or transport them for reuse or disposal. The exact pathway for end-of-life panels is uncertain, since most panels that have been installed to date are still active. One possible complication is that solar installers are often smaller companies and may have gone out of business by the time a system is retired 30-40 years after installation. Another complication is that manufacturers sell to regional distributors in bulk, who then typically sell the modules to installers in multiple states; while there is a prohibition on the sale of modules into the State of Washington, if a manufacturer does not have an approved end-of-life program, and the penalties for doing so ($10,000 per panel installed), are applied to the manufacturer, not the distributor or installer.

4. Solar PV material retirement model

Based on historic sales within Washington, this analysis estimates the capacity and weight of PV modules that will be retired in the state on a yearly basis through 2030. Figure 5 depicts the material flow model used. Assumptions about the lifespan and the failure rate of the modules (i.e. the stock turnover model) were used to predict the timing of retirement of installed panels. Next, the volume and composition of the waste stream was calculated using the average weight of modules within the dataset and the material composition of monocrystalline cells. This information is intended to inform the infrastructure needs for recycling and the economics of material recovery.

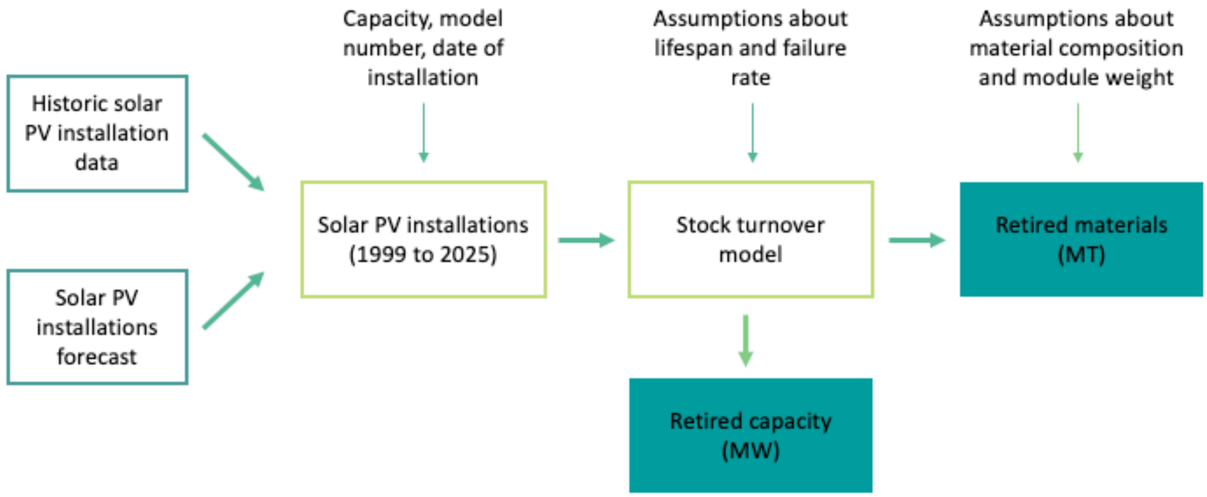

Figure 5:
The MFA model process. The retired capacity is reported in the metric tons of materials retired.

4.1 Data overview for the State of Washington

The data used in this analysis was collected by the Washington State University (WSU) Energy Program for the years of 1999 through mid-2019, reporting a total of 208 MW installed capacity of solar PV modules. This data is for systems installed under one of the State of Washington's renewable energy incentive programs; the WSU Energy Program does not have data for systems installed outside of those programs.[25] The data has been adjusted by adding the 2020 installations reported by SEIA, yielding a total of 264.41 MW installed until 2020. The majority of installations are residential (88%), with the first utility scale facility of 27.78 MW installed in 2018, and a smaller facility of 5 MW in 2020.

The data collected by the WSU Energy Program includes the date of final electrical inspection, city of installation, zip code, utility company interconnection, capacity, and the PV module model number. The most complete data is from July 2017 to June 2019, when the program reporting requirements were expanded to include additional system information. As table 1 demonstrates, 102 MW of all modules reported include the module model code, representing mostly systems that were installed after 2015. The module model codes were used to retrieve additional information, such as the manufacturer, cell type, and module weight. Within this subset, a total of 42 manufacturers have sold into Washington, although in 2018 and 2019 the market is dominated by three companies: Itek Energy (no longer manufacturing in or selling into the state, thus Itek modules are also “orphan” modules, including those sold after July 2017), Hanwha Q-cells, and Silfab since late 2018 (see Figure 6) when they purchased the production facilities from Itek, which then ceased manufacturing modules in the state. It is important to note that Silfab purchased the production line of Itek Energy in Bellingham, WA in 2018 to manufacture Silfab modules, but did not purchase the company or its warranties or liabilities.[26]

Table 1:
Solar PV module installation data used in this analysis.

Total MW installed until 2020	264 MW
Data collected by WSU	208 MW (79% of installations)
WSU data that includes module code	102 MW (39% of installations)

Of the data entries that include module model numbers, the specifics of all modules with at least .3% of the market share have been explored in detail, representing 88% of the market. And, 98% of these modules are monocrystalline, with 1% thin film and 1% of unknown panel technology. This indicates that a high majority of the panels are using monocrystalline technology, an assumption that aligns with the International Technology Roadmap for Photovoltaic.[10] All of the modules are monofacial, which demonstrates a lagging technology adoption of bifacial modules in comparison to the world market.[10]

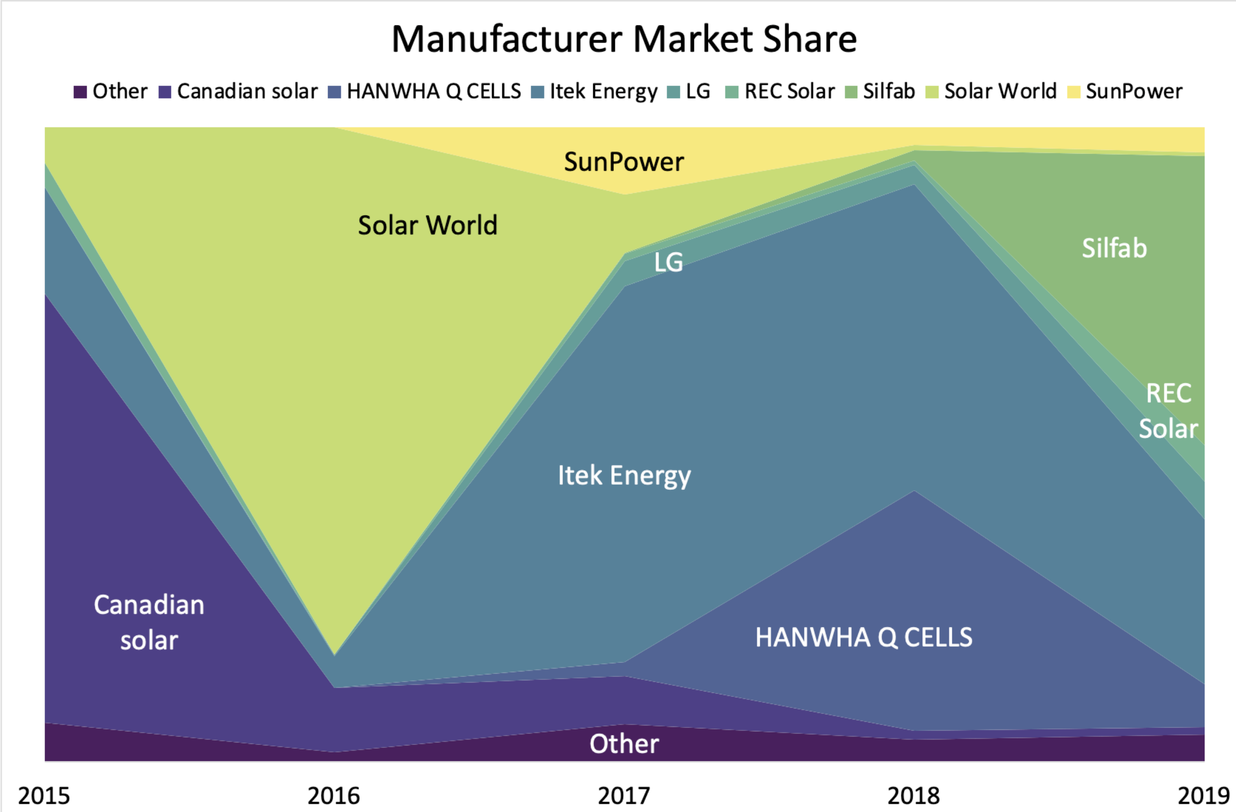

Figure 6:
The market share of manufacturers that have sold into Washington based on the data provided by the WSU Energy Program that contains a module model code (49% of all data). The 'other' category represents manufacturers with less than 5% of the market share.

4.2 Forecast 2020-2025

To provide greater insight into future retirements, the historical data is extended by forecasting future installations through 2025 in Table 1 and Figure 7. High, medium, and low scenarios are used to account for the uncertainty in these estimates.

Table 2:
The forecasted solar PV installation in Washington from 2020 to 2025.

Scenario	Description
High	975 MWs are installed between the years of 2020 and 2025
Medium	834 MWs are installed between the years of 2020 and 2025 based on a forecast from SEIA.
Low	675 MWs are installed between the years of 2020 and 2025

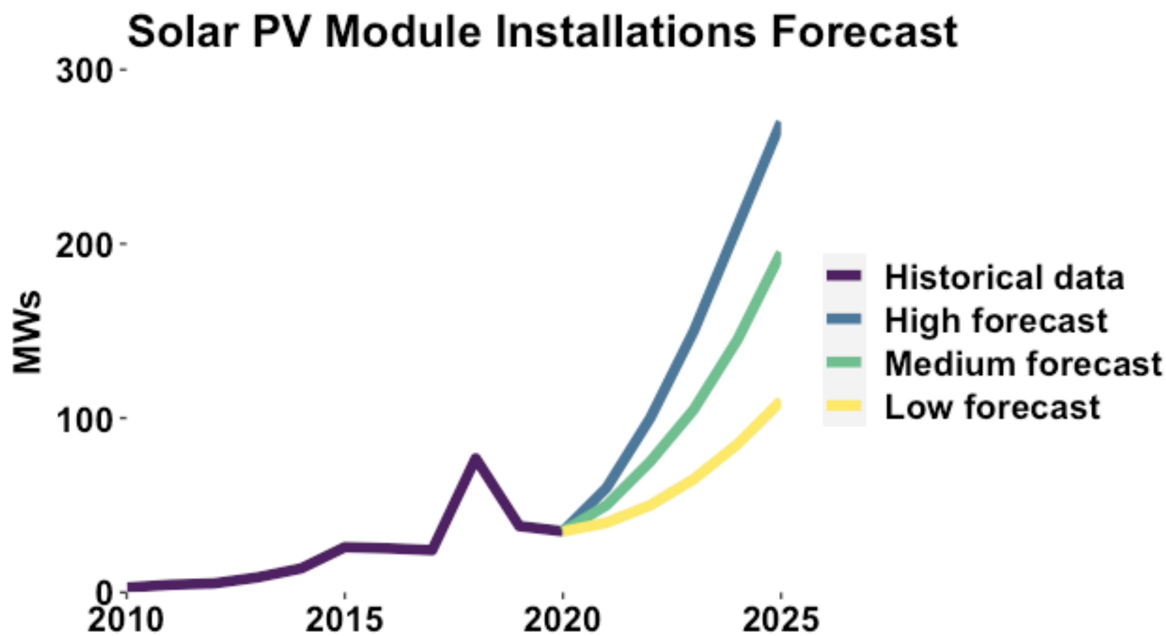

Figure 7:
The solar PV module installation forecast within Washington. Installations until 2020 represent historical installation data, while the medium forecast from 2021 to 2025 are estimates from SEIA.

4.3 Retirement pattern of solar PVs

To estimate the timing of retirement, three possible retirement phases were modelled: early failure, constant accidental failure, and wear-out failure. The retirement pattern indicates that while a small percentage of panels will fail and be retired shortly after installation, due to product malfunction or damage from shipping or installation (“early failure”), the majority of modules will be retired when their output has declined below an acceptable level, due to natural degradation (“wear-out failure”). Wear-out failure is represented by the sharp incline near the average lifespan of the modules. More information on these calculations can be found in the Appendix. Constant accidental failure has a small chance of occurring, but is evenly distributed throughout the lifetime.

Many homes will be reroofed within the lifespan of the modules, which provides an opportunity to replace panels that are broken or not producing at high efficiency, as well as the potential for early failure, due to damage during disassembly and reinstallation. This complication is not included in the failure rates.

The average lifespan of solar PV modules, especially the residential PV systems, is uncertain, despite the extensive research of degradation modes.[27] This is mainly due to the relatively short amount of time modules have been in widespread use, and thus the lack of large-scale retirement or observable performance data under real-world conditions. In addition, determining panel lifespan is challenging because retirement will largely be dictated by the unpredictable behavior of residential consumers, rather than technical performance. Estimates in academic literature vary between 25 and 35 years depending on the analysis and year of installation[28–31], while industry professionals predict a higher lifespan up to 40 years.[14] The product warranty for modules is typically 20 years and the performance guarantee up to 30 years, and it is generally assumed that the panels will continue to be used until they reach 80% capacity or less. A report by DNV GL of the Solar City panels reports that at 35 years the panels will be functioning at 83.5%, while Silfab guarantees their panels will reach 82.6% at 30 years.[32] This high performance suggests that panel lifespan may be longer than their warranty considering a large majority of systems are installed on households that may be less likely to replace working solar panels despite their decreased power output. In practice, the decision to retire a system largely depends on the end customer. If a homeowner chooses to continue to utilize the PV module as it produces 70% or even 60% of its original capacity, then a PV module can last as long as 50 years.

Since it is unknown how long the consumer will keep the panels in use, the retirement model depicts two possible scenarios. The first demonstrates a lifespan of **30 years** and the second represents a longer lifespan of **35 years**, recognizing that these are relatively conservative estimates.

4.4 Material composition

To calculate the total weight of retired modules per year, the average weight in kg-per-Watt of installed modules was calculated for years 2013-2019 based on the weighted average observed in the dataset. For the following years, the average weight is estimated to decrease by 3.5% each year until 2025, continuing the trend of declining material requirements per Watt. This average weight can be found in Table A2 of the Appendix.

Because the vast majority of module installations within Washington are monocrystalline, this analysis uses monocrystalline panel data provided by Silfab to estimate the material composition of a 370-380Wp module, which is shown in Figure 9 and in Table A1 of the Appendix.

5. Results:

5.1 Module retirement

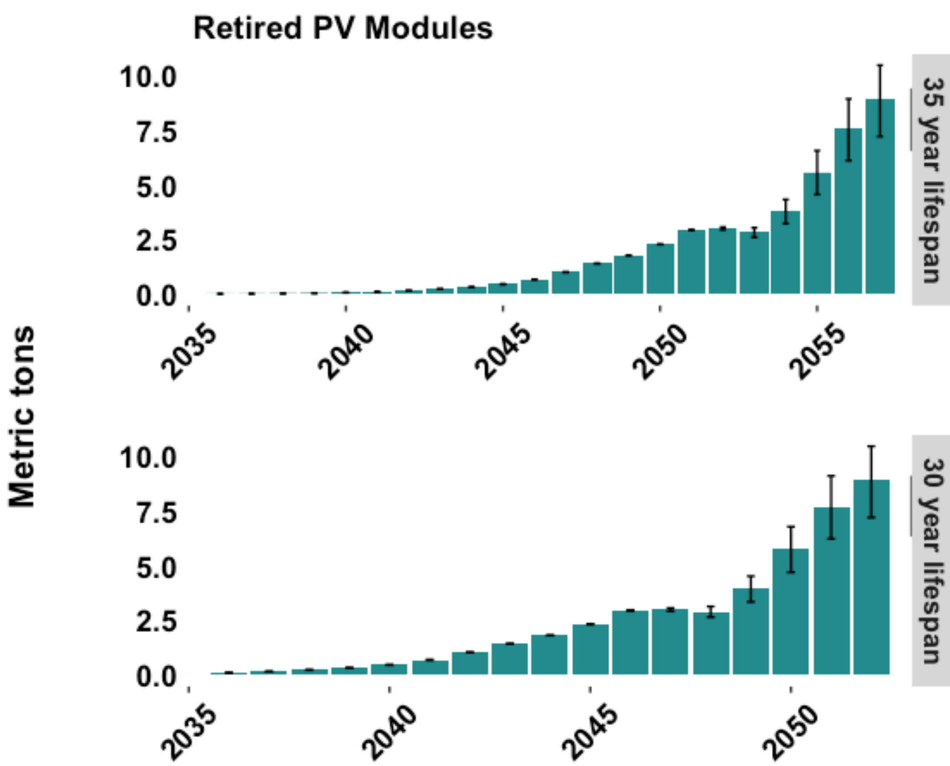

Figure 8:
The metric tons of retired solar PV modules in Washington that are sold between 1999 and 2025. The bars represent the medium sales scenario, while the error bars represent the difference in the high and low sales scenarios.

The forecast estimates the retirement of all modules that were installed up to the year 2025 (Figure 8). In reality, the future retirements will likely continue to rise after 2057, because solar PV installations will continue or increase after 2025. The lifespan of modules impacts the retirement year proportionally to the year differential between scenarios, demonstrating this module retirement will be delayed if the lifespan is increased. The sales scenarios will also impact the retired MTs and is represented by the error bars in Figure 10.

If the modules have a 30-year lifespan, the weight of materials retired reaches 1 MT in 2042 for the medium sales scenario. In 2049, retirement begins to rapidly increase, an expected trend considering this represents about 30 years after solar sales take off. For the years considered, the weight of the waste stream reaches a maximum in 2052 at 7.19 to 10.44 MT, depending on the sales scenario. This is represented in MT and not MW, due to the modules now being a waste stream and not an energy source. If the modules have a 35-year lifespan, the retirement pattern discussed above is moved 5 years later; the retirement per year will reach 1 MT in 2047 for the medium sales scenario. The retirements rapidly increase in 2054 and reach a maximum in 2057 at 7.22 to 10.49 MT, depending on the installation scenario. It is crucial to note these retirements will continue to rise over time past their current peak when planning for recycling and logistics capacity.

5.2 Composition of waste stream

The majority of materials retired consist of glass, aluminum, and encapsulant (see Figure 9). While the type of encapsulant used was not reported by Silfab, the majority of panels use ethyl vinyl acetate (EVA),[10] a substance that is not considered to be toxic.[33] The relatively smaller constituent materials are equally important to consider.

The cell, which represents 4% (about 1.872g/W) of the example panel contains lead, silver, and aluminum. The traces of lead (about .003g/W) represent less than .1% of the panel, although this still presents a risk of leaching if the panels are not properly disposed of (i.e. landfilled). When lead-containing panels are recycled, the sludge will need to be disposed of as hazardous waste.[34] The silver represents less than .3% (about .014g/W) of the panel weight, although it is a valuable material that should be considered for recovery when recycling.

The backsheet represents 3% (about 1.352g/W) of the material and as discussed in section 2.1, there are various materials in use. Silfab, currently the largest distributor of panels in Washington, has stated their products do not contain fluorinated polymers.[14] Considering the historical use of fluorinated polymers within the market, it can be reasonably assumed that panels prior to 2019 contain fluorinated polymers and the use declines as Silfab gains market share and other manufacturers also use fluorine-free backsheets. This is important to note, due to the complications fluorinated polymers add to the disposal process.[35]

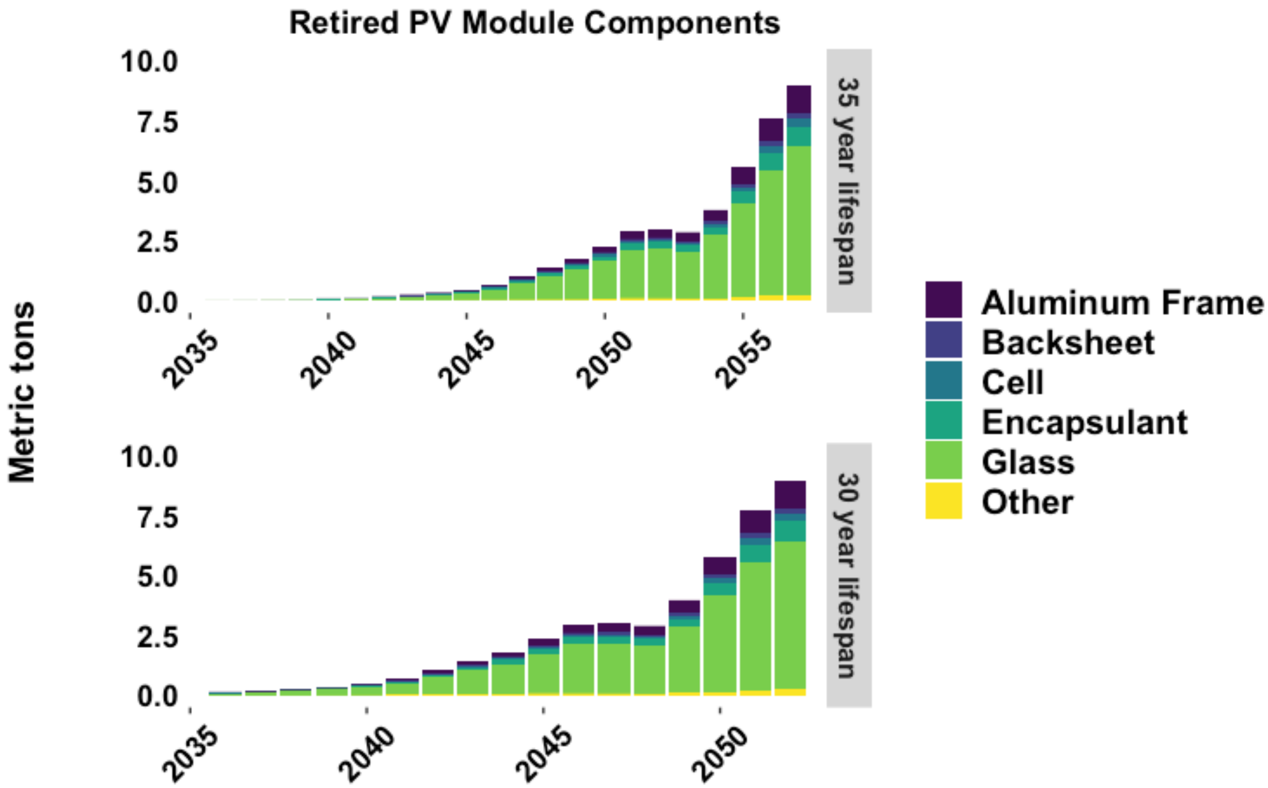

Figure 9:
The metric tons of retired solar monocrystalline PV modules in Washington that are sold between 1999 and 2025. The columns represent the medium sales scenario. Results for the 35-year lifespan scenario in the Table A4 of the Appendix.

5.3 Orphaned modules

Parsing the retired modules by their qualification under HB 1319 demonstrates that the majority of materials retiring will not be covered by the policy until 2045 to 2050. This represents .52 MT covered by the policy and 1.29 MT not covered by the policy in 2044 assuming a 30-year lifespan. Assuming a 35-year lifespan, .46 of 1.78 MT are not covered by the policy in 2049. After these years, the covered panels represent the majority of the retired weight of modules.

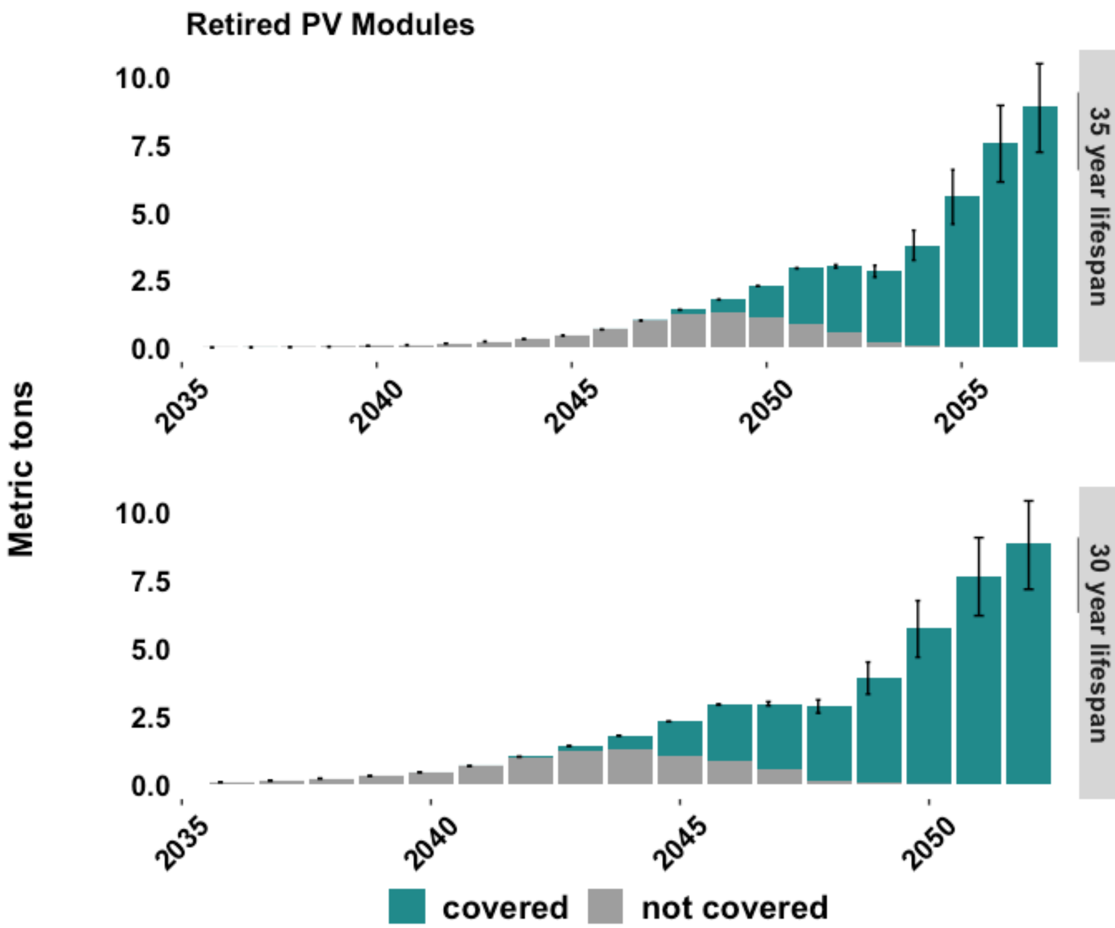

Figure 10:
The metric tons of retired solar PV modules in Washington that are sold between 1999 and 2025 parsed by those panels covered by the legislation and those that are not covered. The bars represent the medium sales scenario, while the error bars represent the difference in the high and low sales scenarios.

Examining the historical data and sales, it is apparent that of total modules sold to date, more than half are not covered by HB 1393 (132.5 MW). Due to the projected increase of sales within the next five years, 83% of all modules installed will be covered by the policy by 2025 in the medium sales scenario, or an estimated 47.86 MT of 56.36 MT.

Table 3: The installed modules in Washington split by qualification under the HB 1319.

Modules **not subject** to regulation	132.5 MW
Modules **subject** to regulation (up to 2020)	131.8 MW
Modules **subject** to regulation (medium forecast 2021 to 2025)	834.0 MW

6. Next steps

This Phase 1 Initial Scoping report provides foundational data on Washington solar PV modules by installation year, manufacturer, and material content, and projects likely module retirement volumes to assess requirements for the implementation of SB 5939 (2017) and subsequent updates from HB 2645 (2020) and HB 1393 (2021). Because of the tight timelines and budget, Phase 1 did **not:**

- address all important information, analysis, and data needs
- include development or assessment of options and recommendations
- seek broad stakeholder engagement in developing and evaluating program design options

Phase 2: Analysis would build on Phase 1 and include at a minimum:

- An analysis of the locations of retirements of pre July 1, 2017 residential PV modules, pre July 1, 2021 utility scale modules, and post July 1, 2017 "orphan" modules not covered by the product stewardship program.
- An overview of the current structure, capacity, and possible evolution of the existing PV module value chain in Washington including manufacturers, distributors, installers and other actors. This will include an assessment of how to best align key product stewardship program roles and requirements (tracking installations, educating end users, collection and transport, processing and funding) with Washington's supply chain.
- An assessment of current PV module recycling infrastructure, recycling processes and related costs (if available) for removing, disassembling, transporting, and processing PV modules at end-of-life. This includes infrastructure available for both pre- and post-July 1, 2017 modules, and whether those systems would be synergistic or separate.
- An assessment of the costs, risk, and opportunities of developing a Washington PV module product stewardship program that meets the requirements of SB 5939 and subsequent legislation. Key issues include:
    - Manufacturer participation in Washington Market
    - Availability and pricing of PV Modules
    - Long term environmental impacts
- Review and follow-up of product stewardship and other programs identified in sections 2.2 and 2.4 of the report to assess best practices and whether these practices are transferrable to the Washington market.

Optional analysis extension that may be considered include:

- Completing a comprehensive cost-benefit analysis for stewardship program options including:

  - The value of recovered materials
  - The cost to implement stewardship, including administration, storage, and transportation
  - Economic (job impacts)
  - Net environmental benefits
- Assessing whether extending the stewardship program should be expanded to address the entire PV installation (for example, battery storage, inverter, and controls)

Phase 3: Complete an analysis for options to meet the intent of Washington's Solar PV module stewardship legislation. The analysis will address:

- Long term sustainability and feasibility
- Impacts on prices and availability of PV modules
- Life cycle environmental
- Options for addressing orphan (non-covered) modules
- Expanded stakeholder engagement to solicit input into policy development and review program design recommendation(s). Stakeholder engagement should include manufacturers, distributors, recyclers, and environmental advocacy groups.

7. Conclusion

This analysis has demonstrated that the volume of end-of-life solar PV panels expected to enter the waste stream will reach 1 MT in 2042-2047, depending on the expected lifespan. Slightly over half of the modules retiring at this time will not be covered by the existing product stewardship policy, suggesting that the state will need to develop a plan and potentially funding to manage orphaned panels.

Further research is needed to accurately predict the exact composition of the waste stream, due to a lack of available data and an accelerated timeline. This study has roughly estimated future materials using a sample bill of materials for a monocrystalline module and applied it to all panels. As a result, it does not capture the variability of module composition based on manufacturer and year of production, nor does it account for potential trends and improvements in module design beyond a decreasing module weight (kg/kWh). However, while the specifics may vary, it is likely to remain the case that close to if not over 85% of retired materials will be glass and aluminum. While the proportions vary by year and manufacturer, the sample bill of materials demonstrates 81% of the module weight consists of aluminum and glass, and the International Renewable Energy Agency (IRENA) forecasts that these materials will represent over 85% by 2030. This indicates that as it is currently written, the 2019 Product Stewardship Plan produced by Ecology may not encourage the recovery of key elements of interest such as silicon, copper, or silver; the Plan states that the manufacturers must recycle at least 85% of the modules by weight, which is nearly met through recycling the aluminum and glass alone.

Enhanced solar installation data that enables tracking the location and characteristics of installed modules is recommended, similar to the tracking that was done for certain installations by the WSU Energy Program. Further study should also seek to analyze retirements spatially to inform infrastructure needs and planning. Finally, more qualitative information on the logistics of decommissioning, collecting, and recycling solar PV systems is recommended. In particular, a stakeholder engagement process is suggested to solicit information about the current end-of-life path and parties involved. This will help policymakers identify gaps, as well as avoid duplicating existing efforts.

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Appendix

Table A1:

The composition of an HC Product provided by Silfab. Represents a 1000V, 1762x1037x35mm M6-9BB 120 Half-Cell.

Component	Grams/375 Wp
Cell	702
Aluminum - long frame	1462
Aluminum - short frame	838
Aluminum - frame corner keys	48
Glass	13200
Front encapsulant	813
Back encapsulant	903
Backsheet	507
Junction box and cables	Unknown
JB silicon adhesive	38
Interconnect wire – coated copper-round wire	134
PV bus-bar coated copper	60
Frame silicone adhesive	155

Table A2:

The weight (kg/W) of solar PV modules per year. To calculate the total weight of retired modules per year, the average weight in kg-per-Watt of installed modules was calculated based on the weighted average observed in the dataset for the years 2013 to 2019[1]. After 2019, the average weight is estimated to decrease by 3.5% each year until 2025, based on the historical efficiency increase by Silfab of a 7% kg/W reduction from 2019 to 2021. Prior to 2013 there is also expected to be an increase of 3.5% kg/W yearly.

Year	kg/W	Year	kg/W	Year	kg/W
2010	0.077	2016	0.063	2022	0.052
2011	0.074	2017	0.062	2023	0.050
2012	0.072	2018	0.065	2024	0.049
2013	0.069	2019	0.058	2025	0.047
2014	0.067	2020	0.056		
2015	0.065	2021	0.054		

[1] From the data, the specification of all modules representing over .3% of the market share, a total of 27 different models of modules and representing 88% of the market, have been explored in detail.

To estimate the timing of retirement, a bathtub-shaped retirement pattern was used to model three phases of retirement: early failure, constant accidental failure, and wear-out failure. The failure rates used in this analysis are taken from an analysis performed by Peeters et al. (2017) (Table A3) and the probability of failure was calculated using equation 1.

Table A3:
The failure rates for the early failures and the constant failures.[30]

Phase	Failure Rate
Early failure- 1st year	.00006
Early failure- 2nd year	.00018
Early failure- 3rd year	.00017
Constant failure ≥ 4th year	.000051

The probability of failure per year of use (*P*), taking into account the panel installation year (*s*) and the year of failure (*w*), is calculated using equation 1 and adapted from Peeters et al. (2017). This equation uses the average lifespan (*e*) discussed in section 4.3 and the failure rate (r) which depends on the phase in Table A1. The standard deviation (f) is estimated to be 3, similarly to Peeters et al. (2017).

$$P = r + \frac{1}{f\sqrt{2\pi}} e^{-\frac{(w-s-e)^2}{2f^2}} \tag{1}$$

The failed MW per year (*FM*) is then calculated by multiplying the MW installed each year *(i)* by the failure rate per year of use throughout the potential lifespan of the module.

$$FM = \sum P_s * i_{s,w} \tag{2}$$

Table A4:
The retirement of components from 2040 to 2060 for the medium sales scenario and assuming the panels have a 35-year lifespan. All results are in metric tons.

Year	Covered by the Policy?	Aluminum Frame	Cell	Glass	Encapsulant	Backsheet	Other
2041	covered	0.30	0.09	1.70	0.22	0.07	0.06
2041	not covered	12.40	3.71	69.69	9.06	2.68	2.67
2042	covered	0.30	0.09	1.70	0.22	0.07	0.06
2042	not covered	19.19	5.74	107.88	14.02	4.14	4.13
2043	covered	0.30	0.09	1.70	0.22	0.07	0.06
2043	not covered	28.16	8.42	158.31	20.58	6.08	6.06
2044	covered	0.31	0.09	1.72	0.22	0.07	0.07
2044	not covered	39.31	11.75	220.99	28.73	8.49	8.45
2045	covered	0.35	0.11	1.98	0.26	0.08	0.08
2045	not covered	55.53	16.60	312.18	40.58	11.99	11.94
2046	covered	0.76	0.23	4.30	0.56	0.17	0.16
2046	not covered	82.09	24.54	461.50	59.99	17.73	17.65
2047	covered	3.42	1.02	19.21	2.50	0.74	0.73
2047	not covered	120.98	36.17	680.10	88.41	26.12	26.02
2048	covered	15.84	4.74	89.08	11.58	3.42	3.41
2048	not covered	157.34	47.04	884.52	114.99	33.97	33.84
2049	covered	56.99	17.04	320.37	41.65	12.31	12.26
2049	not covered	162.70	48.64	914.67	118.91	35.13	34.99
2050	covered	145.96	43.64	820.54	106.67	31.52	31.39
2050	not covered	135.91	40.64	764.08	99.33	29.35	29.23
2051	covered	252.07	75.36	1417.07	184.22	54.43	54.21
2051	not covered	111.17	33.24	624.99	81.25	24.01	23.91
2052	covered	299.60	89.58	1684.32	218.96	64.69	64.43
2052	not covered	72.32	21.62	406.54	52.85	15.61	15.55
2053	covered	325.96	97.45	1832.48	238.22	70.38	70.10
2053	not covered	23.17	6.93	130.24	16.93	5.00	4.98
2054	covered	458.69	137.14	2578.66	335.23	99.04	98.64
2054	not covered	9.56	2.86	53.72	6.98	2.06	2.06
2055	covered	688.40	205.82	3870.07	503.11	148.65	148.05
2055	not covered	1.68	0.50	9.47	1.23	0.36	0.36
2056	covered	936.07	279.87	5262.42	684.12	202.12	201.31
2057	covered	1106.58	330.84	6220.99	808.73	238.94	237.98

Table A4 Continued

Year	Covered by the Policy?	Aluminum Frame	Cell	Glass	Encapsulant	Backsheet	Other
2058	covered	1007.77	301.30	5665.47	736.51	217.61	216.73
2059	covered	533.03	159.36	2996.56	389.55	115.10	114.63
2060	covered	82.90	24.79	466.07	60.59	17.90	17.83